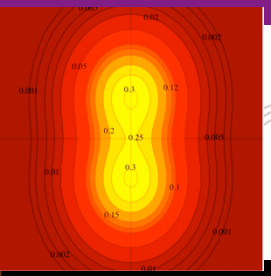
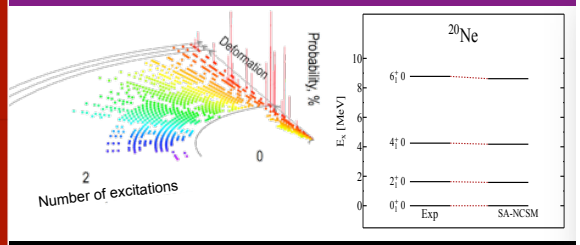
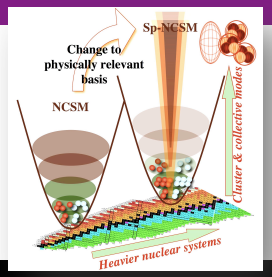
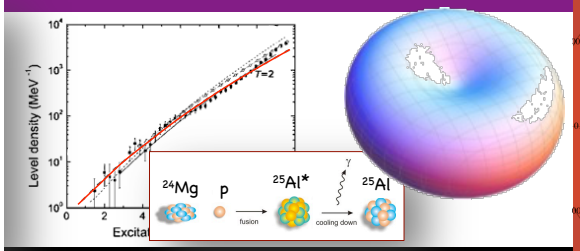
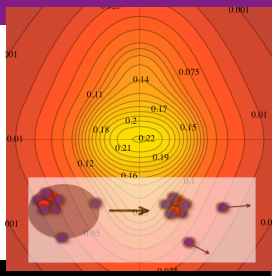









Electromagnetic sum rules and observables from the ab initio symmetry-adapted no-core shell model

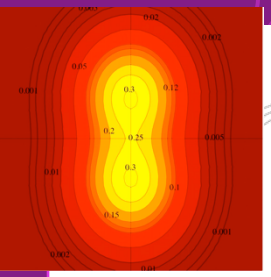
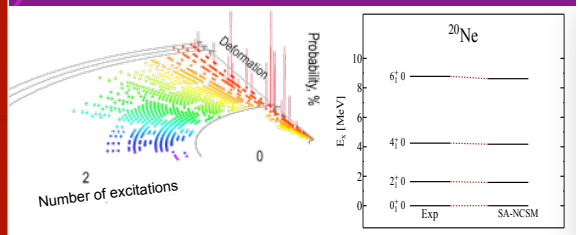
Kristina Launey … LSU Team … **Jerry Draayer, Tomas Dytrych,**
Alexis Mercenne
Robert Baker, Ali Dreyfuss,
David Kekejian, **Grigor Sargsyan**,
Madeleine Miora

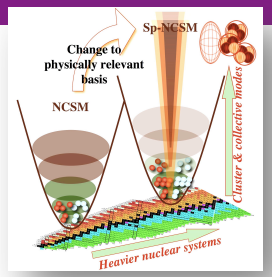
In collaboration with
Sonia Bacca & Nir Nevo Dinur
Princeton U. – W. Tang & B. Wang
Czech Republic – D. Langr & T. Oberhuber

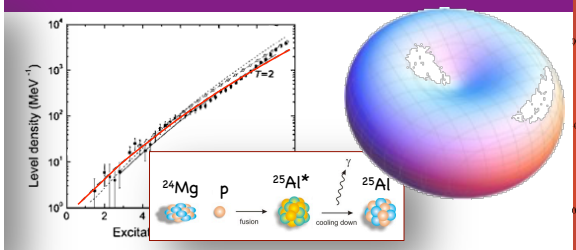
HPC Resources
NSF/U. of Illinois …*BlueWaters*
LSU…*SuperMike-II*

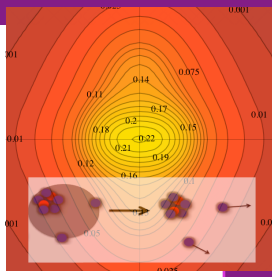
Supported by NSF & DOE

LSU







2N Force 3N Force 4N Force

LO $(Q/\Lambda_\chi)^0$

NLO $(Q/\Lambda_\chi)^2$

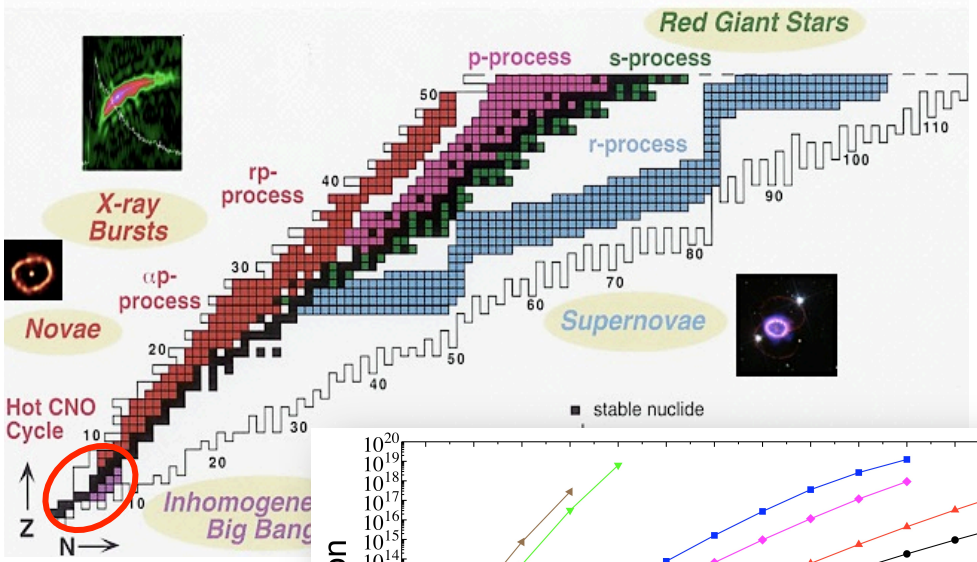
NNLO $(Q/\Lambda_\chi)^3$

N^{3}LO $(Q/\Lambda_\chi)^4$

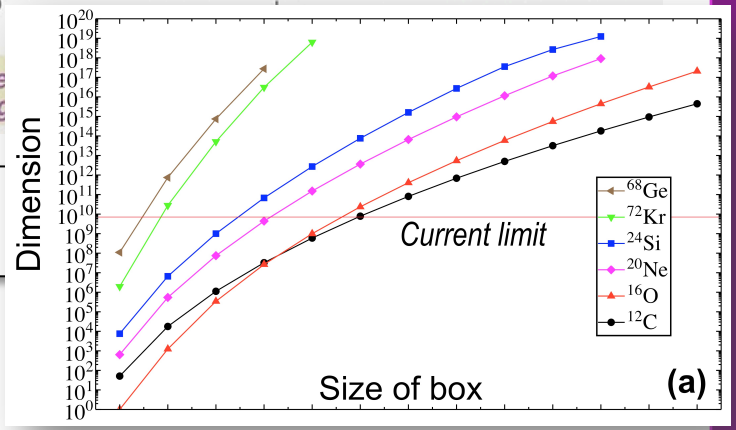
N^{4}LO $(Q/\Lambda_\chi)^5$

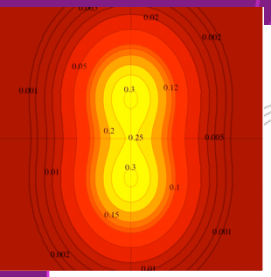
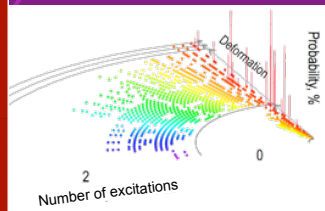
Chiral Interactions

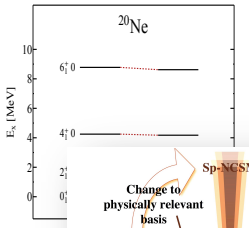
Weinberg, van Kolck, Machleidt, Entem, Meissner, Epelbaum, Krebs, Bernard,…

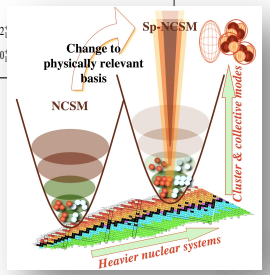


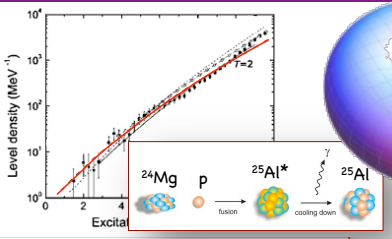
No-core Shell Model (NCSM)

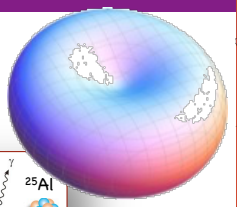
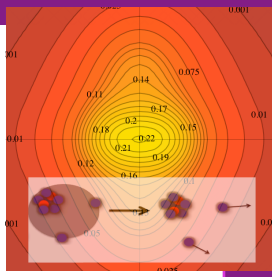


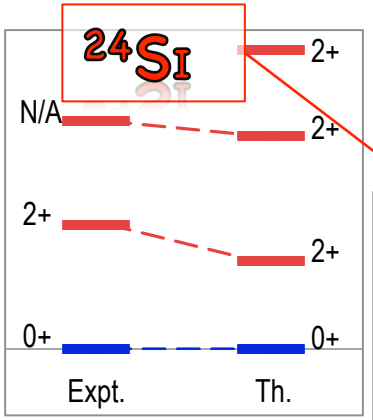


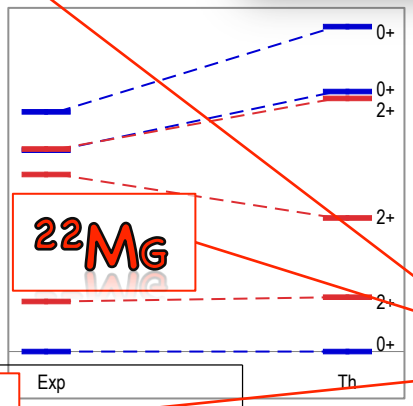


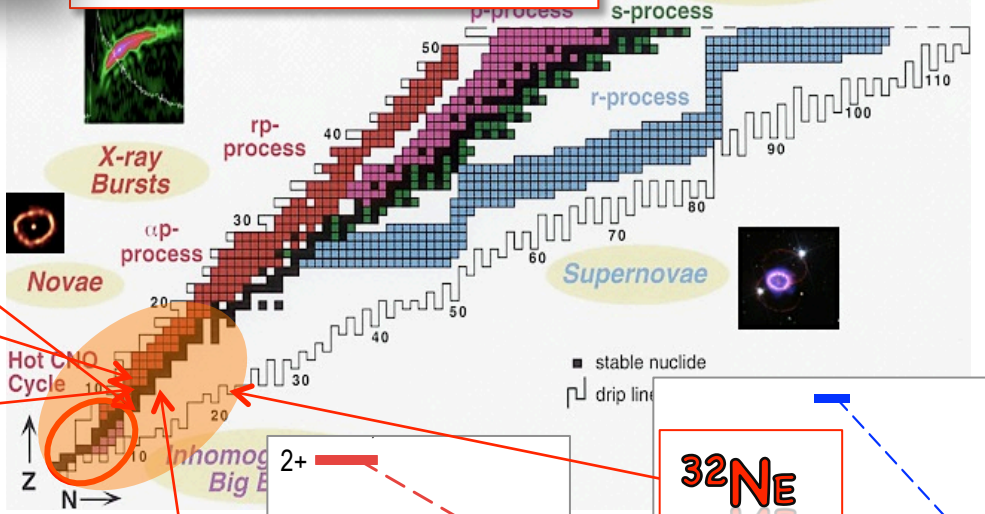


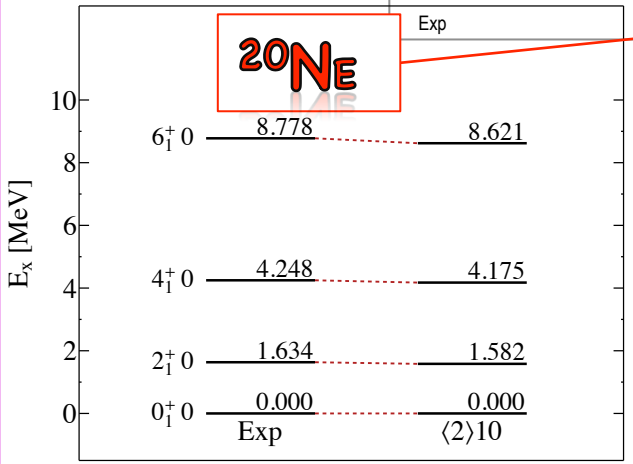



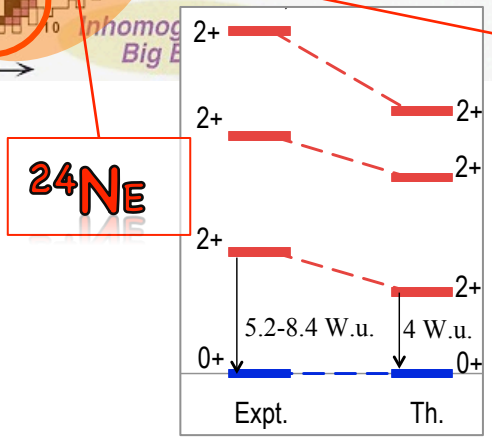
Symmetry-adapted No-core Shell Model (SA-NCSM)

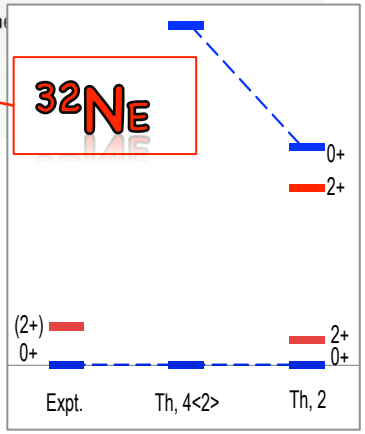


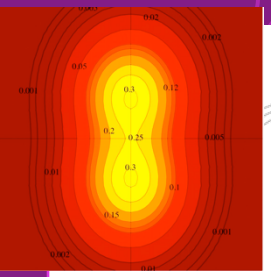


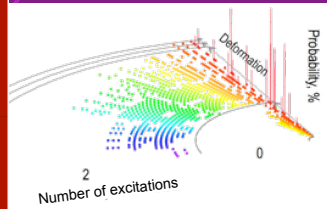


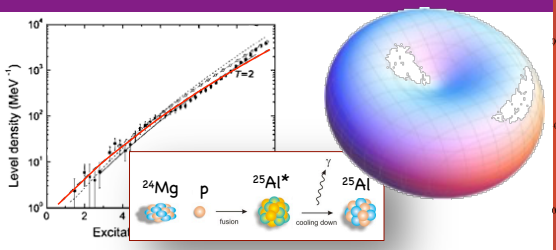


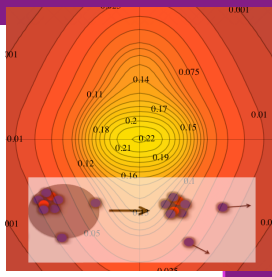


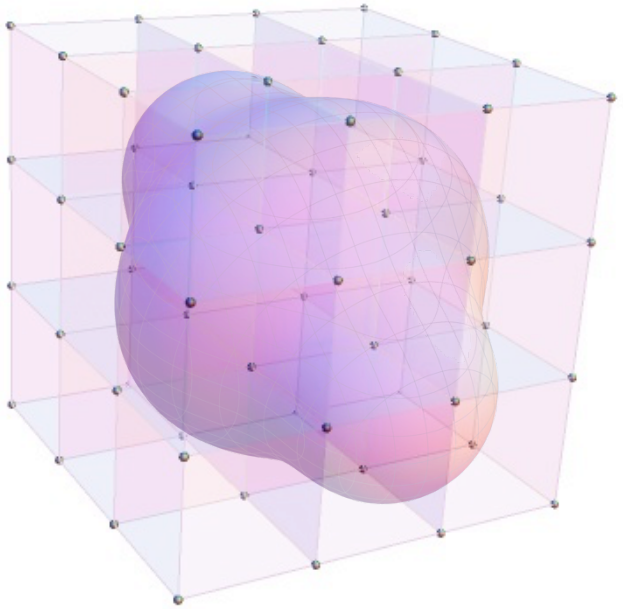






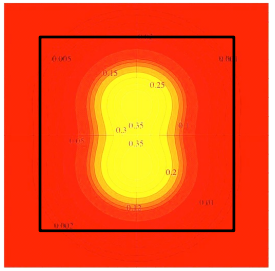






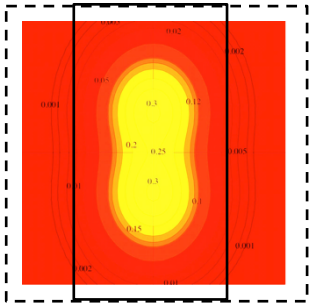
NCSM

Total HO quanta
N_{max}



SA-NCSM

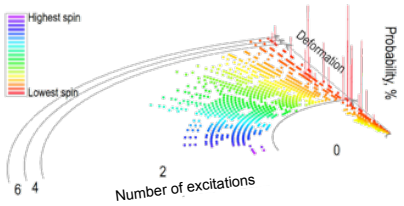
Total HO quanta
N_{max}
+
Distribution:
z, x, y

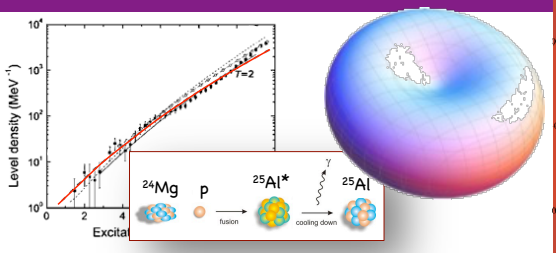


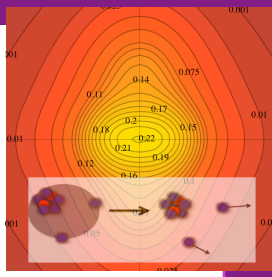
LSU code (LSU3shell): sourceforge.net/projects/lsu3shell

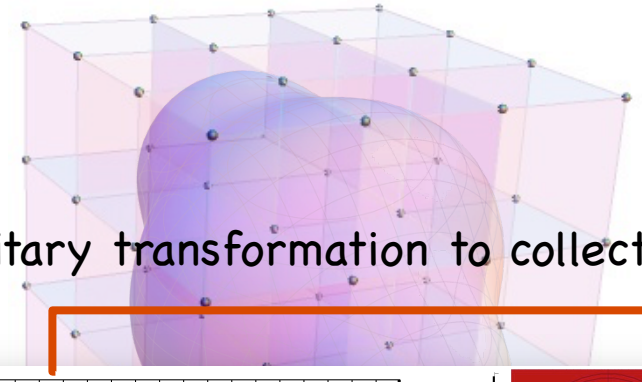
Dytrych et al., Phys. Rev. Lett. 111 (2013) 252501

Launey et al., Prog. Part. Nucl. Phys. 89 (2016) 101



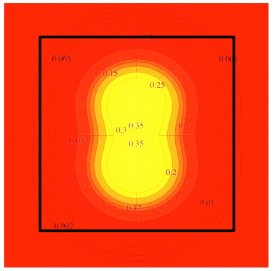






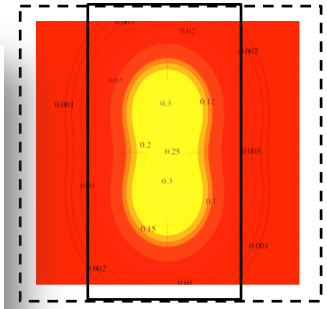
NCSM

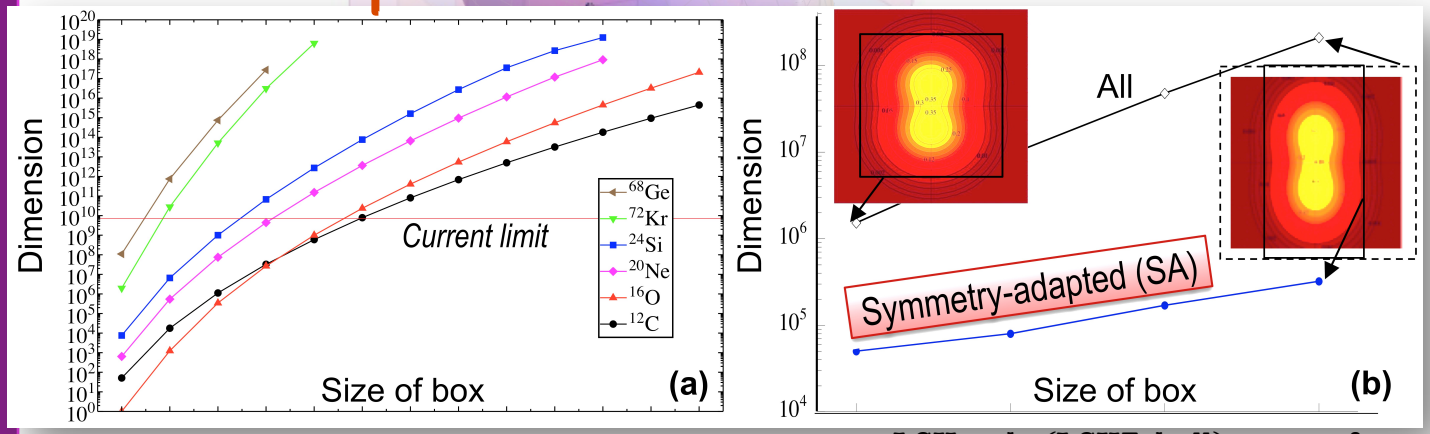
Total HO quanta
N_{max}



Unitary transformation to collective basis (Sp)

SA-NCSM





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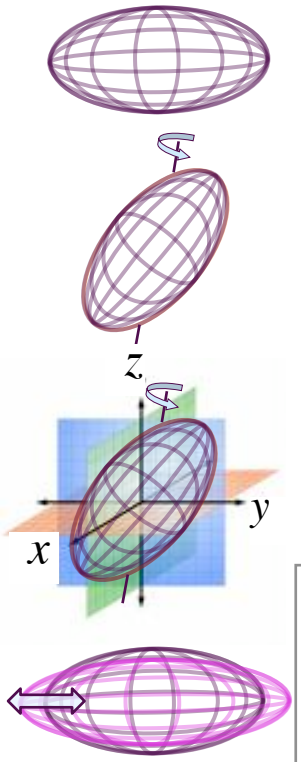
Dytrych et al., Phys. Rev. Lett. 111 (2013) 252501

Launey et al., Prog. Part. Nucl. Phys. 89 (2016) 101

What physics can we learn from Sp basis?

Sp (collective) basis configuration:



one equilibrium deformation (``shape")

rotations

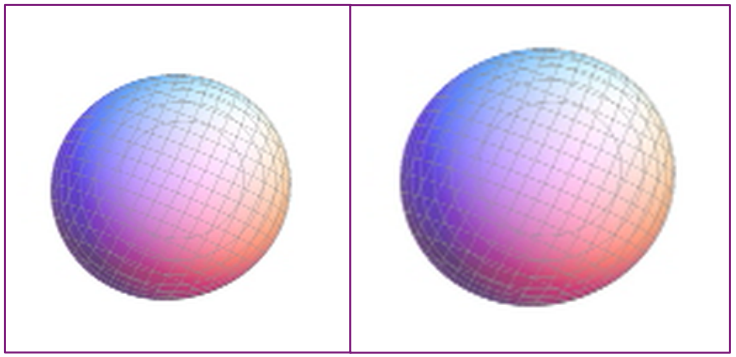
space orientation

Vibrations

(of the giant resonance monopole (r^2)/ quadrupole (Q) type)

All states preserve the equilibrium shape...

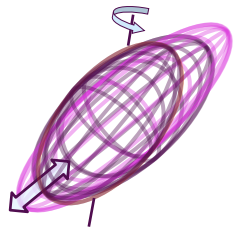
Symmetry?



Symplectic Sp(3,R) Symmetry!

Formal definition

All linear canonical transformations of the single-particle phase-space observables

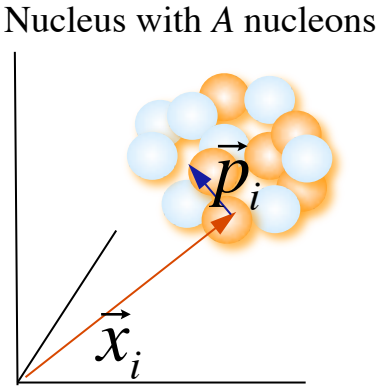


$$x_{i\alpha} \rightarrow \sum_{\beta=x,y,z} a_{\alpha\beta} x_{i\beta} + b_{\alpha\beta} p_{i\beta}$$

$$p_{i\alpha} \rightarrow \sum_{\beta=x,y,z} c_{\alpha\beta} x_{i\beta} + d_{\alpha\beta} p_{i\beta}$$

that preserve the canonical commutation relation

$$\left[x_{i\alpha}, p_{j\beta}\right] = i\hbar\delta_{ij}\delta_{\alpha\beta}$$



Generators:

$$Q_{ij} = \sum_n x_{ni} x_{nj},$$

$$S_{ij} = \sum_n (x_{ni} p_{nj} + p_{ni} x_{nj}),$$

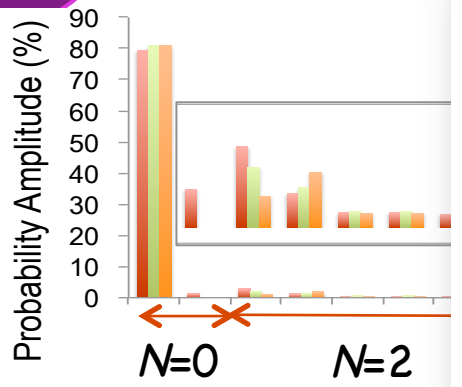
$$L_{ij} = \sum_n (x_{ni} p_{nj} - x_{nj} p_{ni}),$$

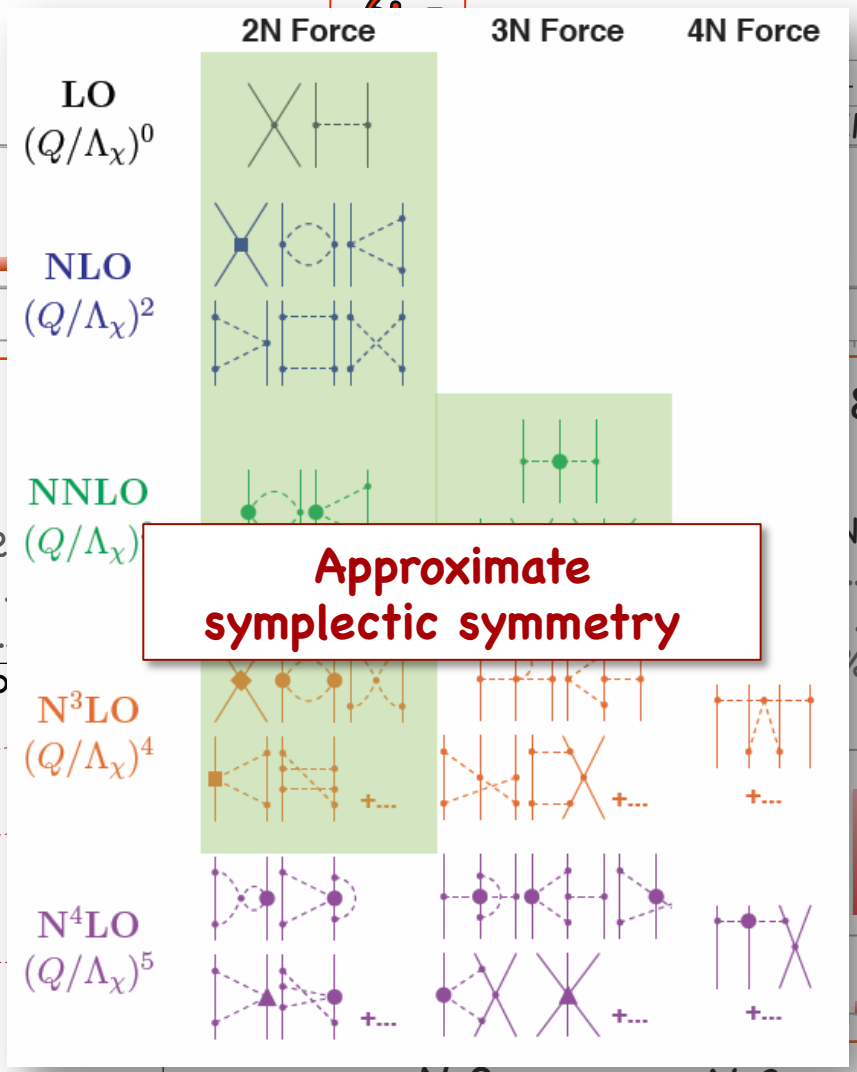
$$K_{ij} = \sum_n p_{ni} p_{nj},$$

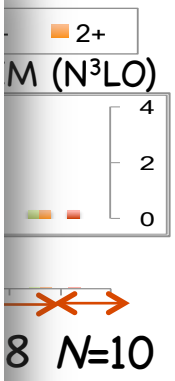
SU(3) in a HO shell (Elliott, 1958)

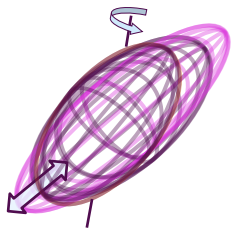
Rowe, Rosensteel, Draayer, Hecht, Suzuki, Escher, Bahri, ….

Novel Approximate Symmetry



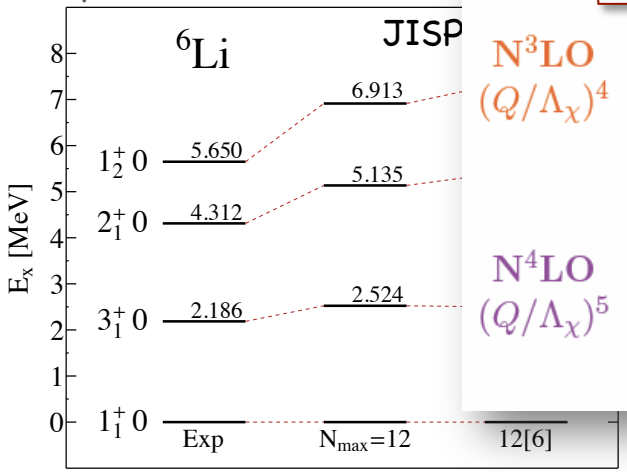




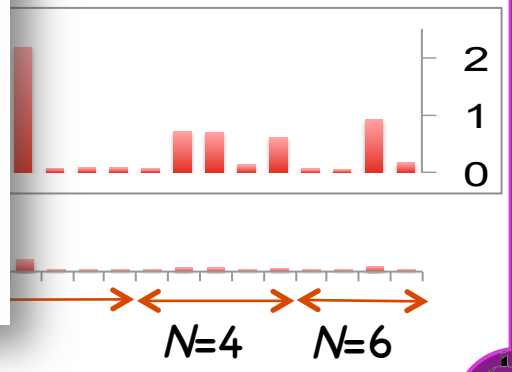


⁶Li, Nmax=12
J=1,2,3 states……2
Sp(3,R) irreps……
Sp(3,R) with P>0.2%……

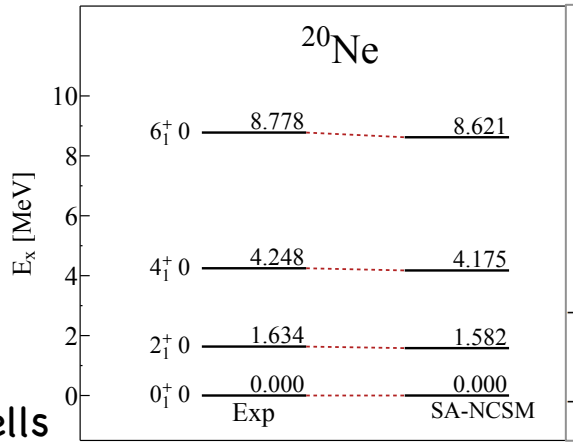
Nmax=8
…2x10¹¹
…1,392
%: ….27

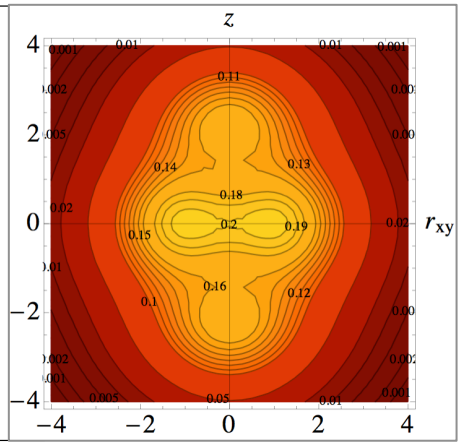


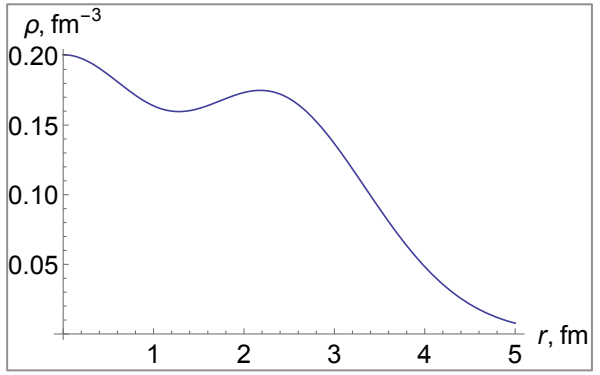
²⁰Ne
EM (N³LO)



Collectivity features





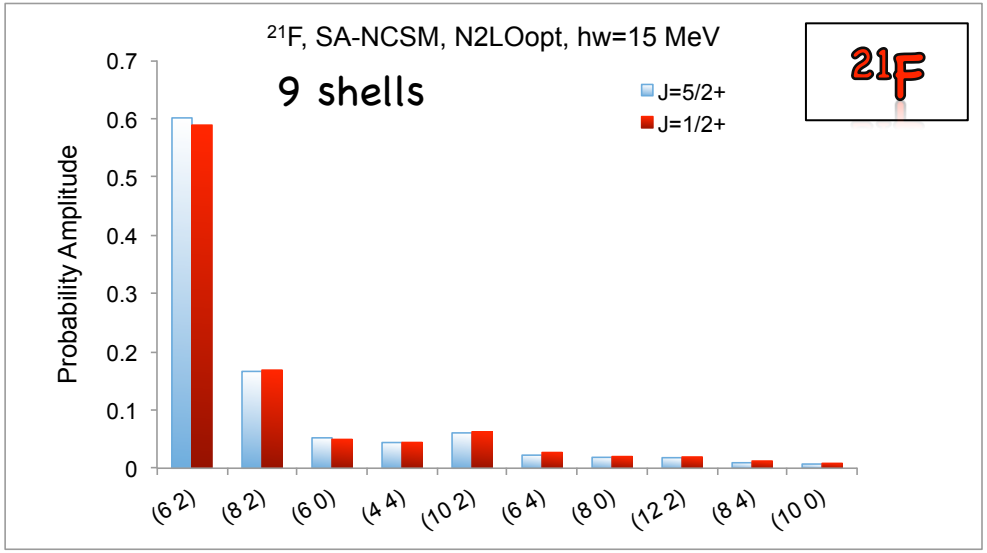


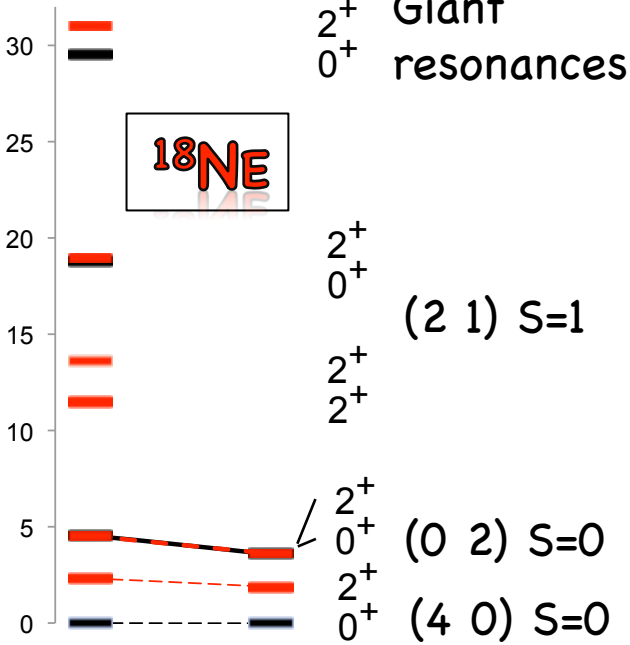
13 shells

SA-NCSM (selected model space): 50 million SU(3) states

Complete model space: 1000 billion states

Ne & Mg isotopes

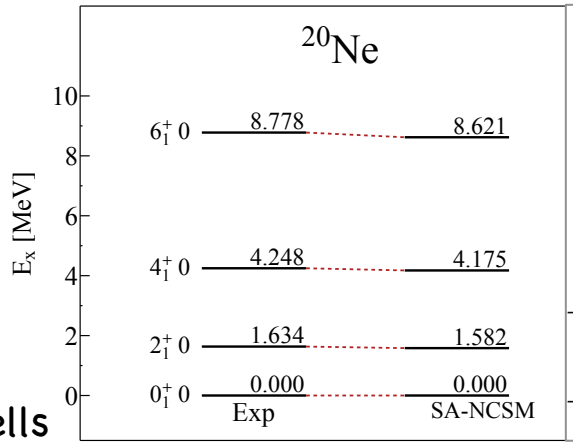


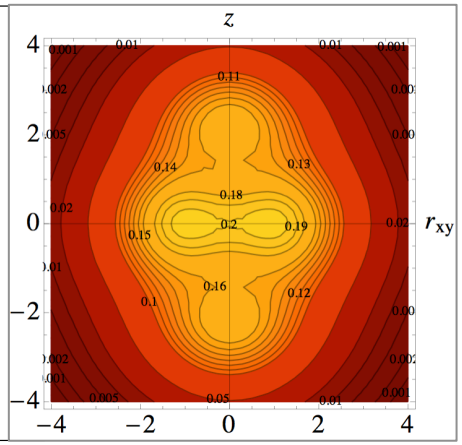


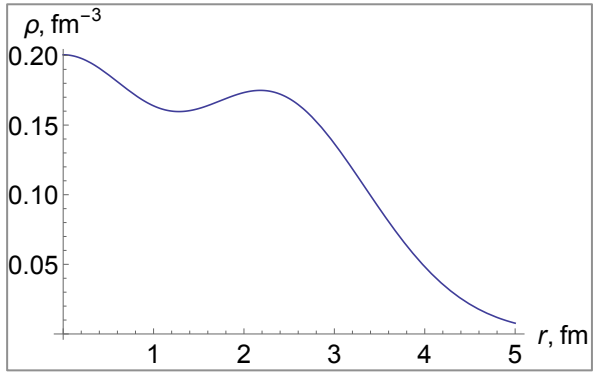
Grigor Sargsyan, PhD student, LSU

N2LOopt; 9 shells

Collectivity features







13 shells

SA-NCSM (selected model space): 50 million SU(3) states

Complete model space: 1000 billion states

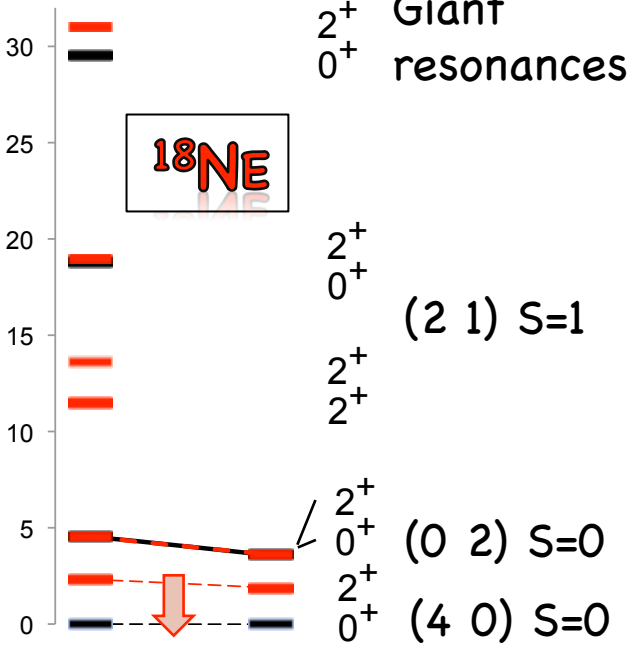
Ne & Mg isotopes

^{18}Ne, B(E2: $2^+ \rightarrow 0^+$)

Experiment…… 17.7(18) W.u.

9 shells …… 1.13 W.u.

33 shells ……. 13.0(7) W.u.
(no effective charges)



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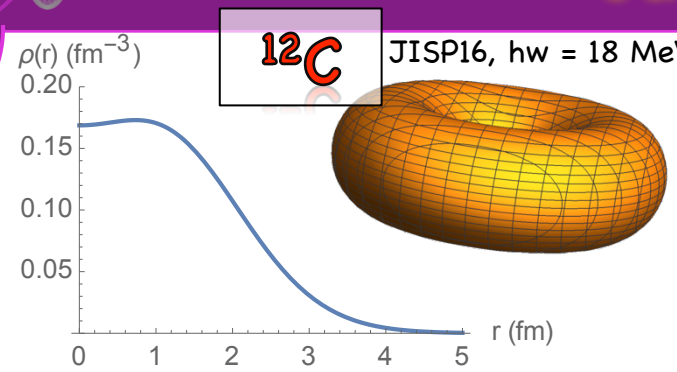
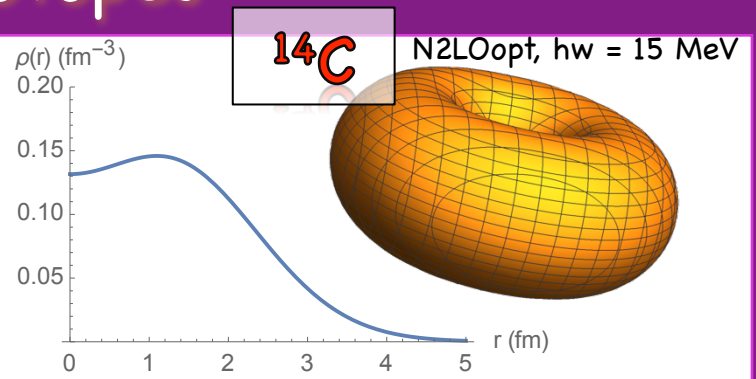
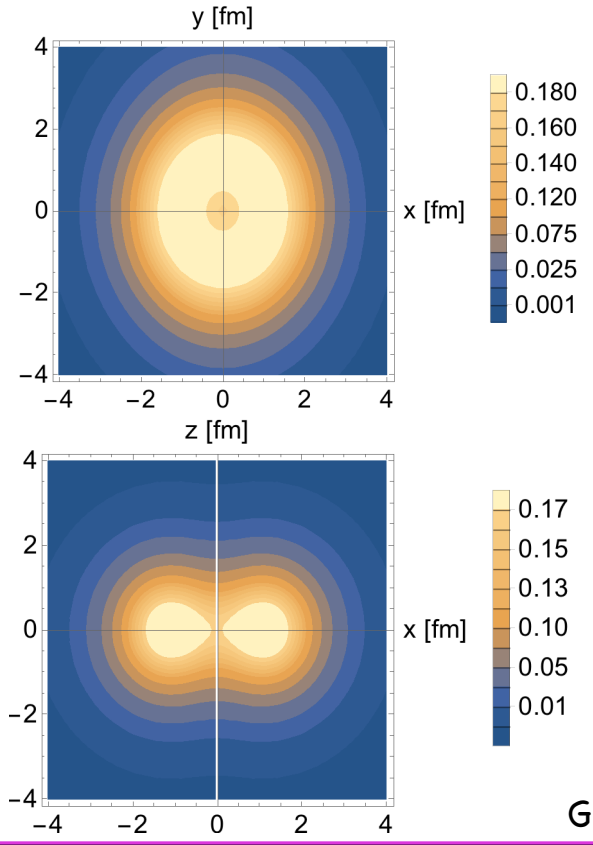
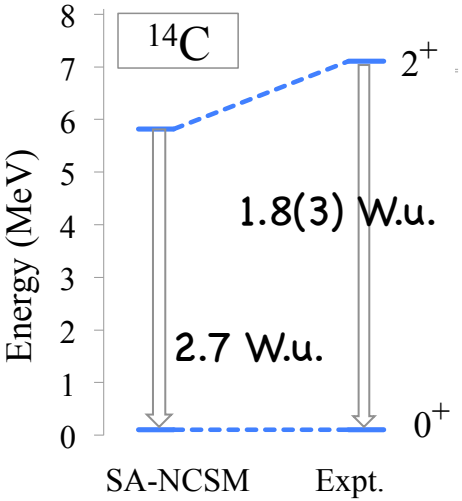
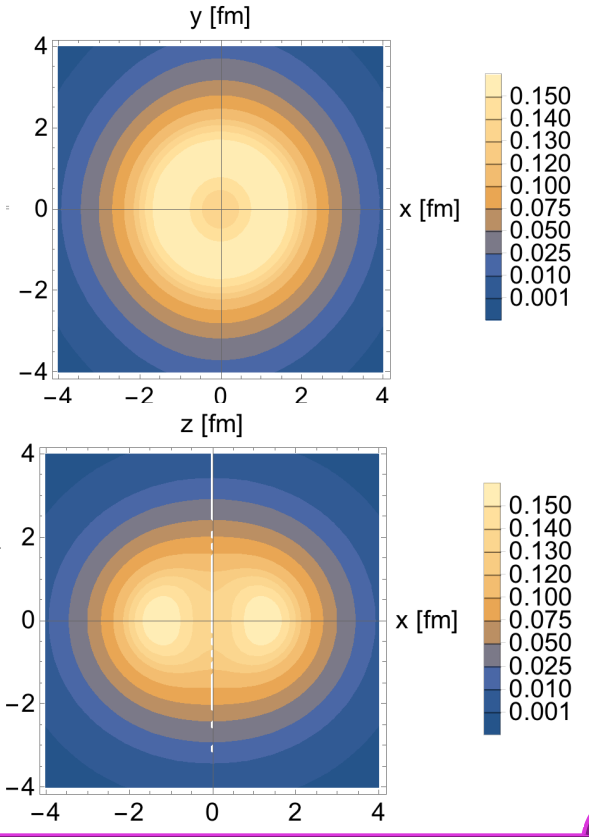
Carbon isotopes











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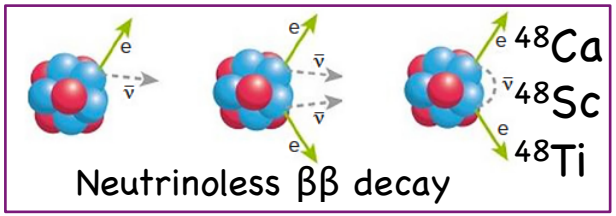
Structure of Ca-48 and Ti-48

^{48}Ca



Neutrinoless ββ decay

^{48}Ti

8 shells, N2LOopt

0^+

SA-NCSM (selected): ……966,152

Complete model space: ……3,162,511,819

2^+

SA-NCSM (selected): ……3,055,554

Complete model space: …14,522,234,982

8 shells, N2LOopt

0^+

SA-NCSM (selected): ……602,493

Complete model space: …..24,694,678,414

2^+

SA-NCSM (selected): ……1,178,834

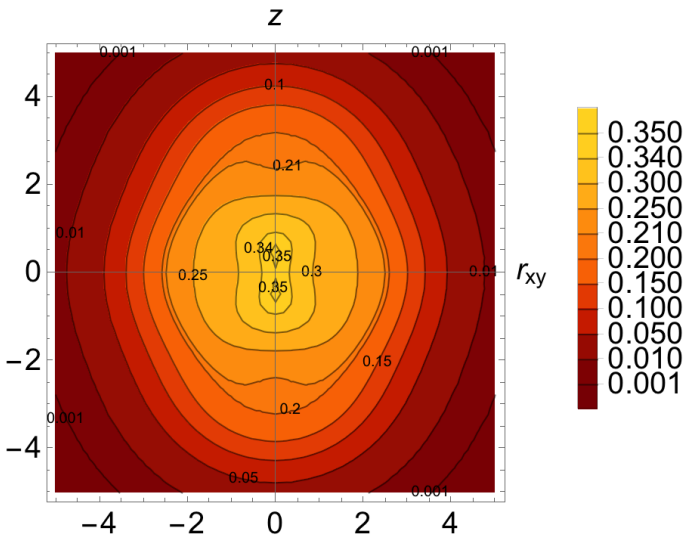
Complete model space: …113,920,316,658

^{48}Ti, $Q(2^+)$ [e fm^2]

Experiment…… -17.7

8 shells …… -19.3

(no effective charges)



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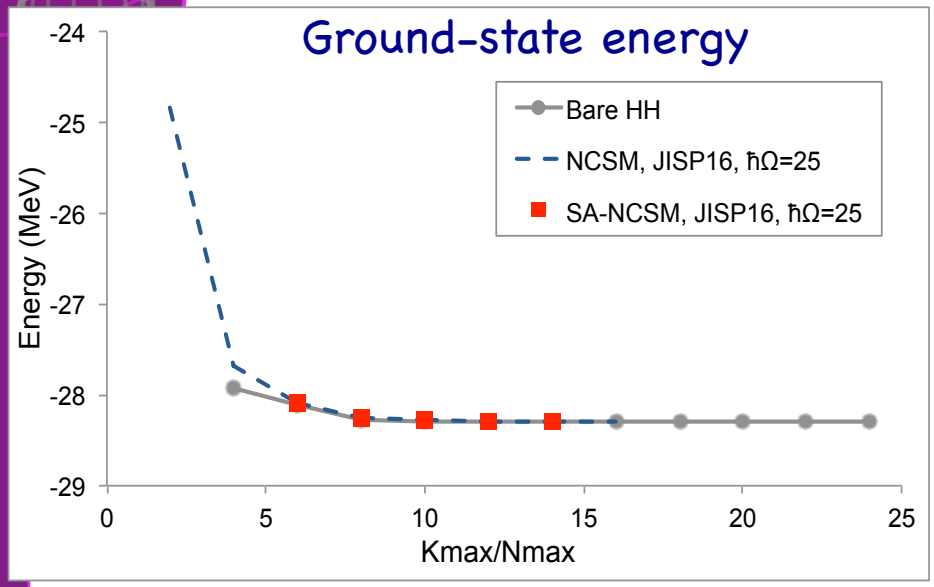
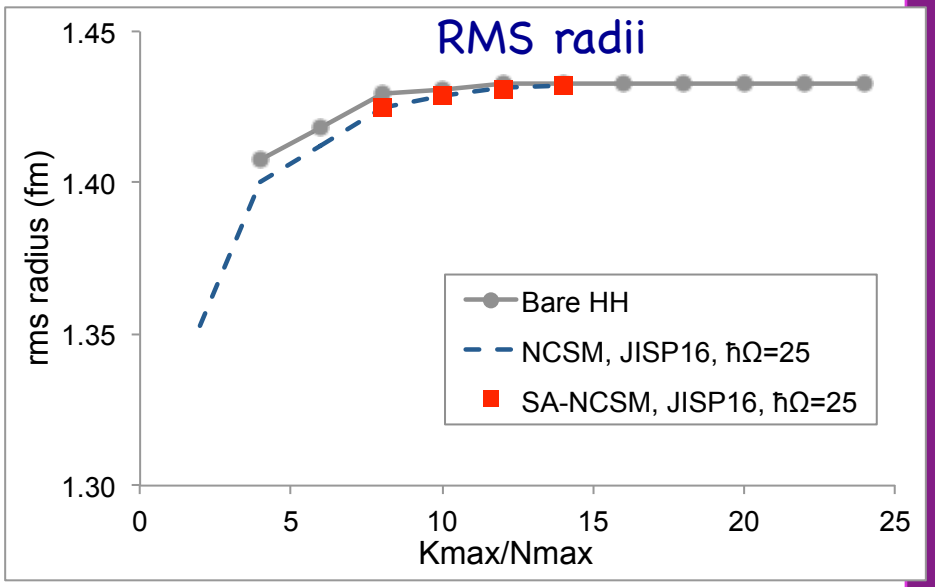
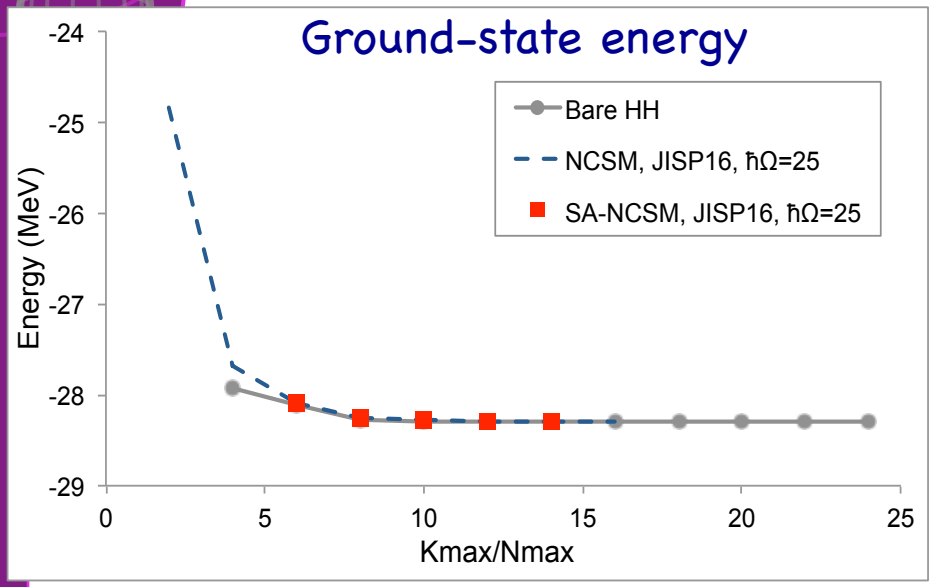
HH and SA-NCSM benchmark: ^{4}He

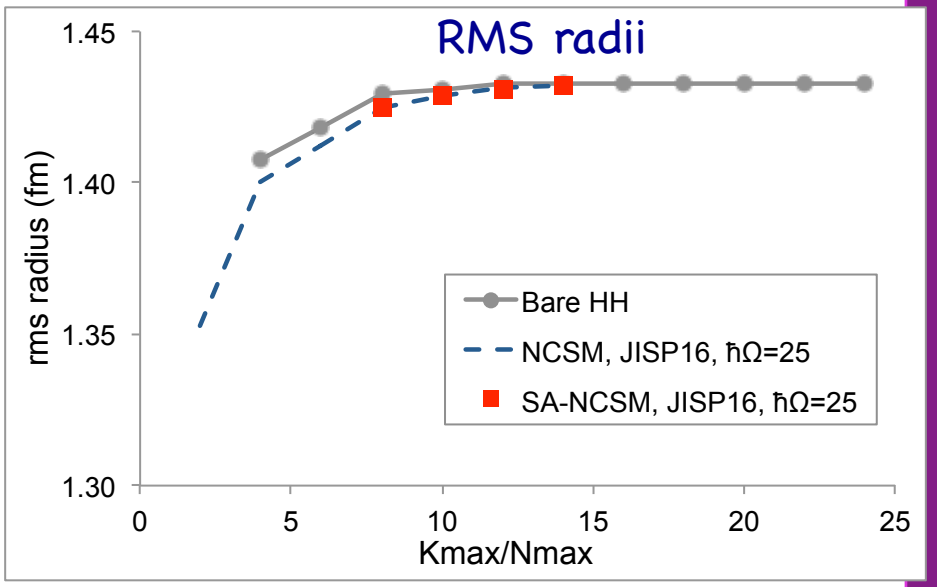


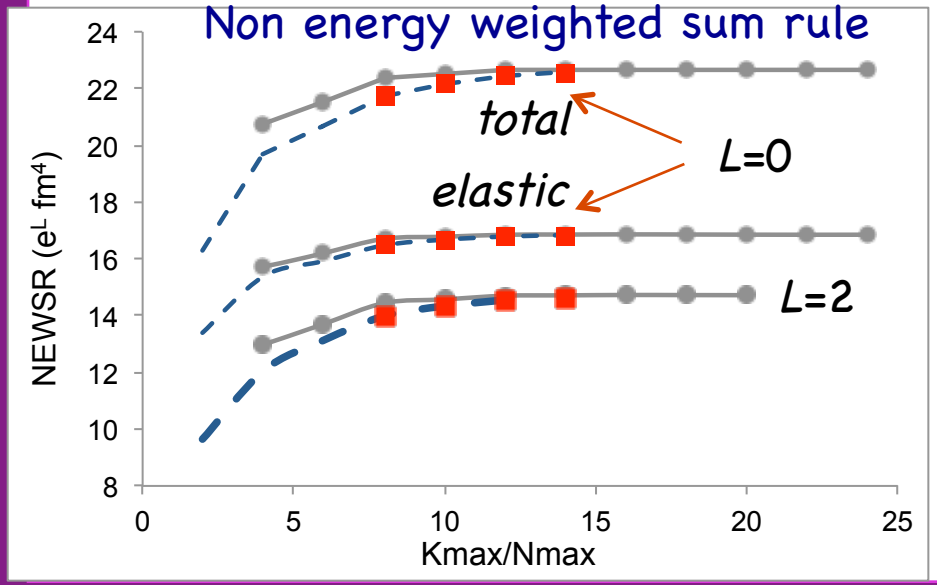


Baker et al., in preparation (2018)

HH and SA-NCSM benchmark: ^{4}He







Response function

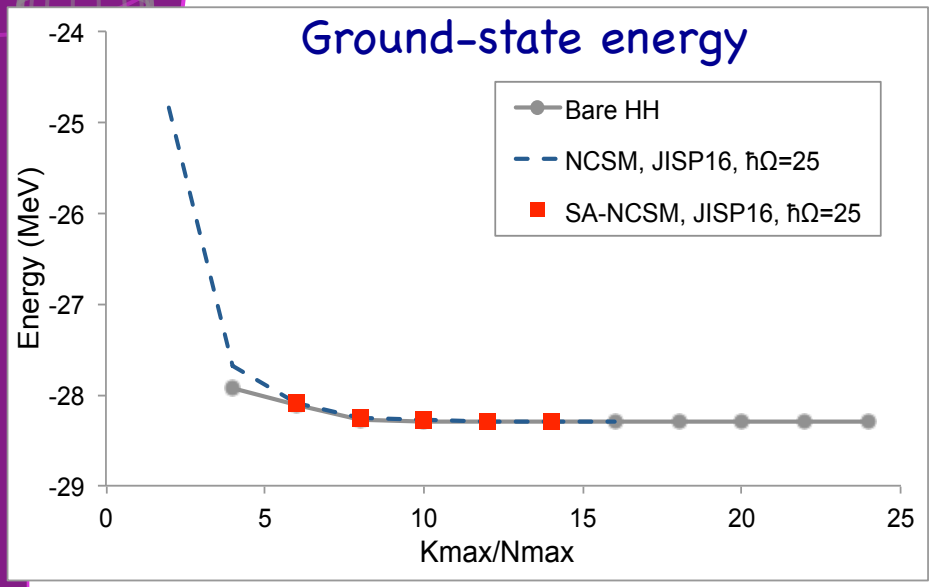
$$R(\omega) = \sum_f \left| \left\langle \psi_f \left| \Theta \right| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

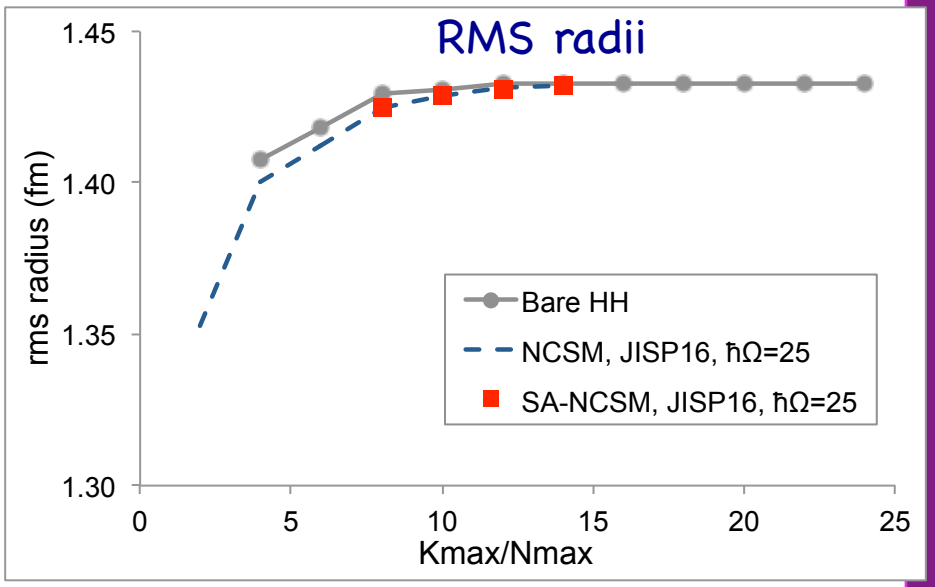
Sum rules

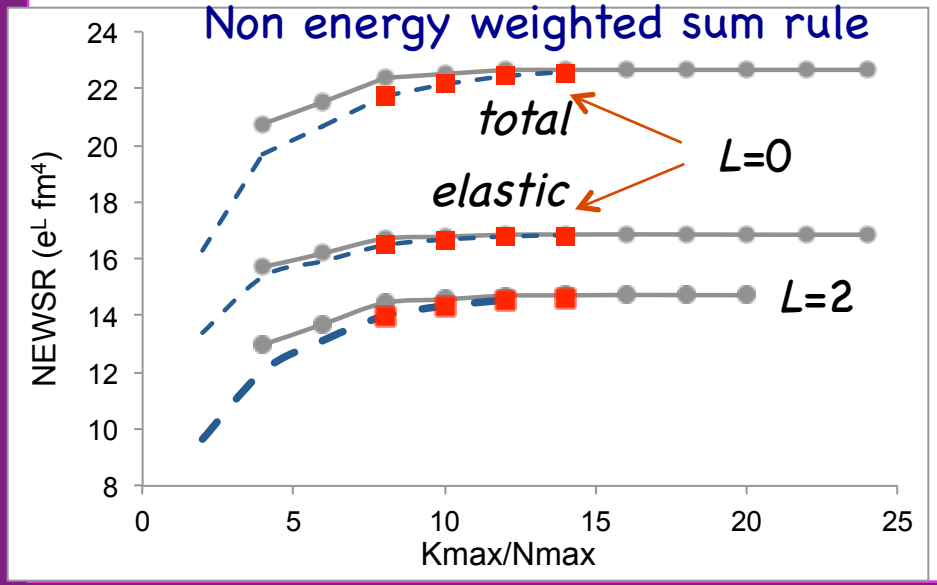
$$m_n = \int_0^\infty d\omega \; \omega^n R(\omega)$$

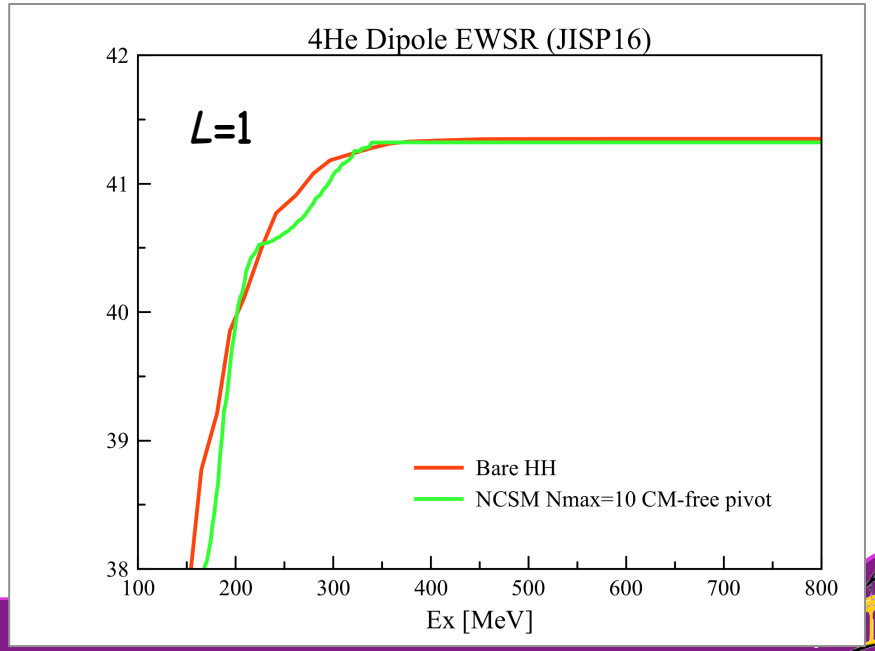
Baker et al., in preparation (2018)

Sum rules for ^{4}He: HH and SA-NCSM benchmark

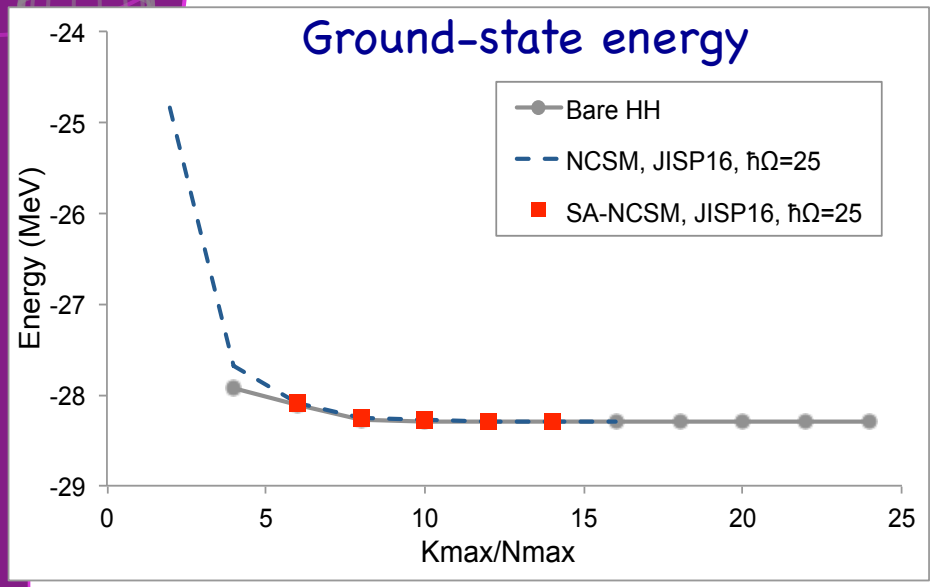


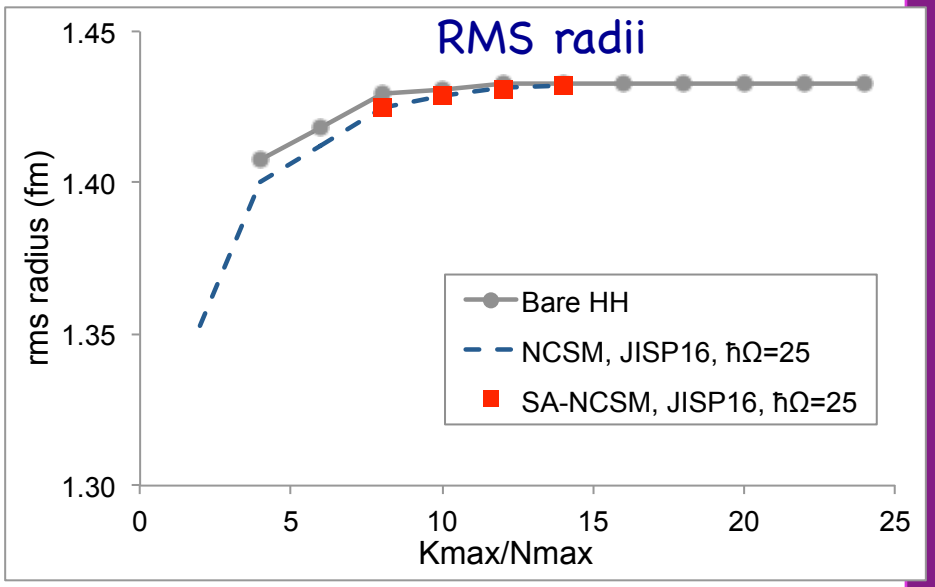


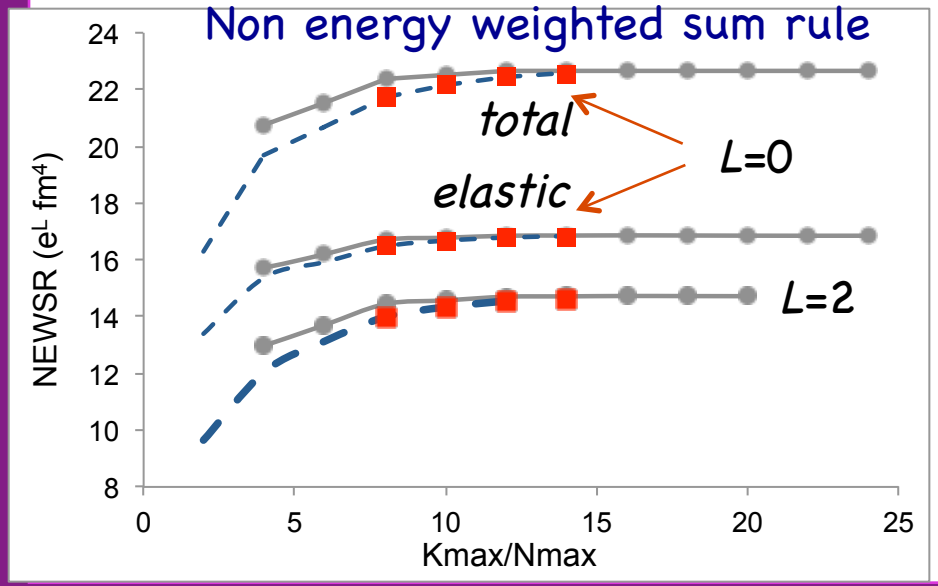


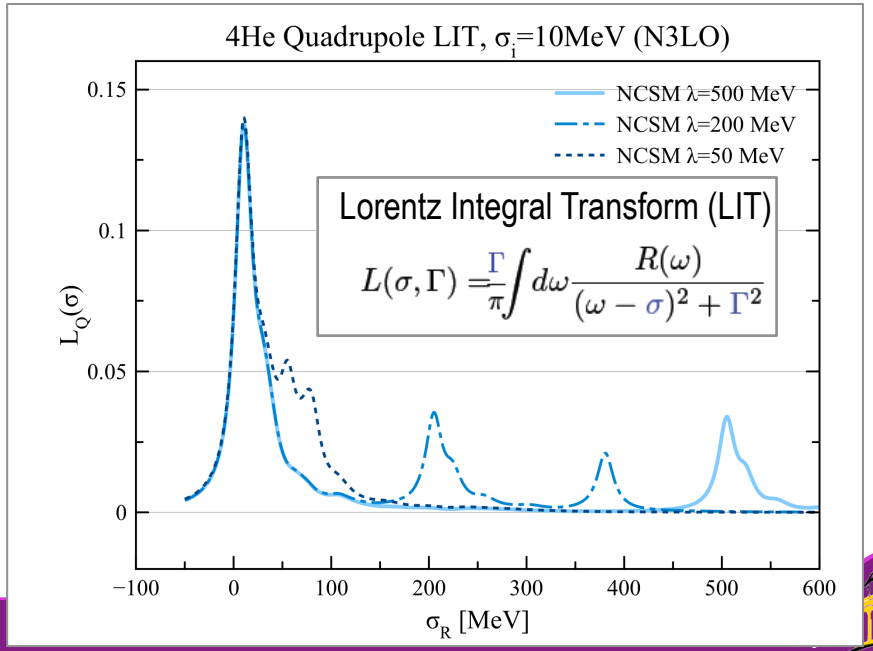


Sum rules for ^{4}He: HH and SA-NCSM benchmark





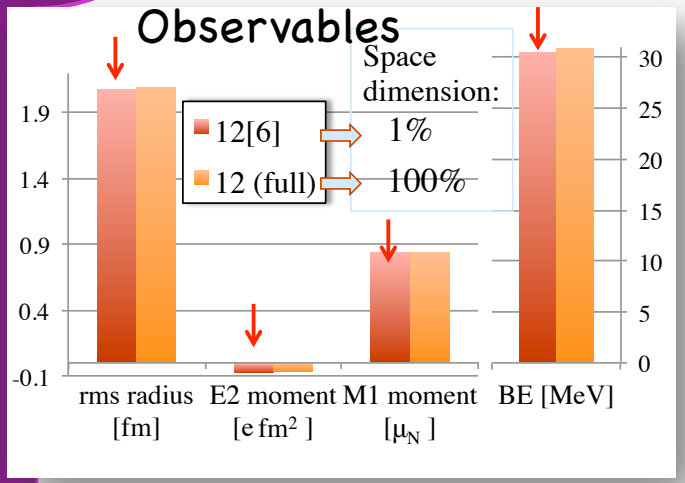




Efficacy of SA-NCSM

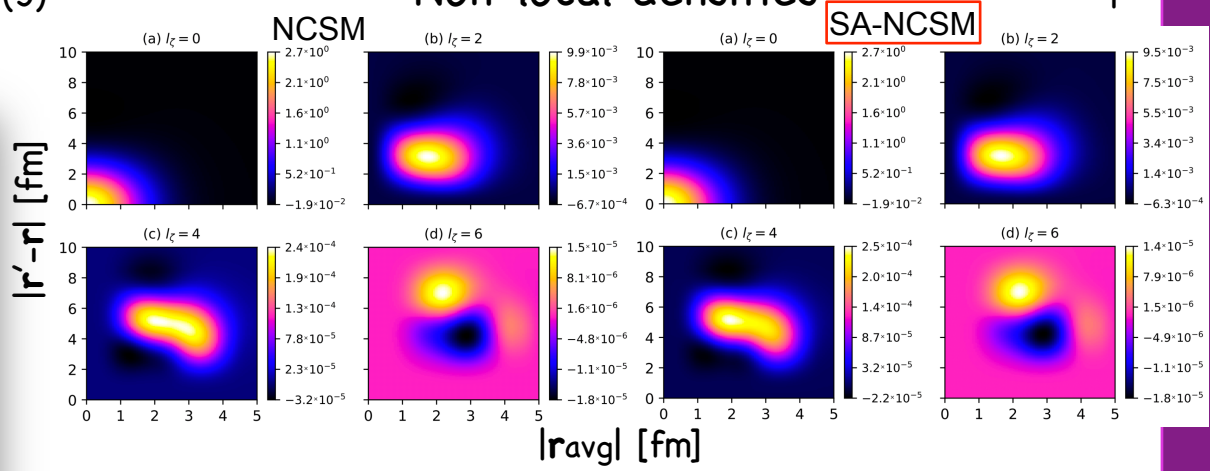
^{6}Li

SA-NCSM, SU(3)

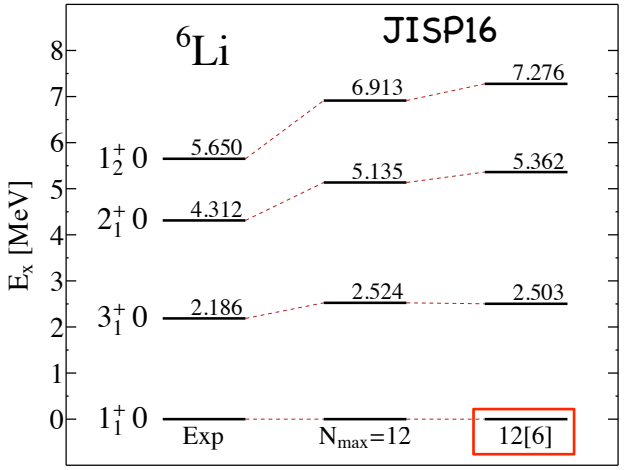


Non-local densities

N2LOopt



Burrows, Elster, Popa, Launey, Nogga, Maris, Phys. Rev. C 97 (2018) 024325

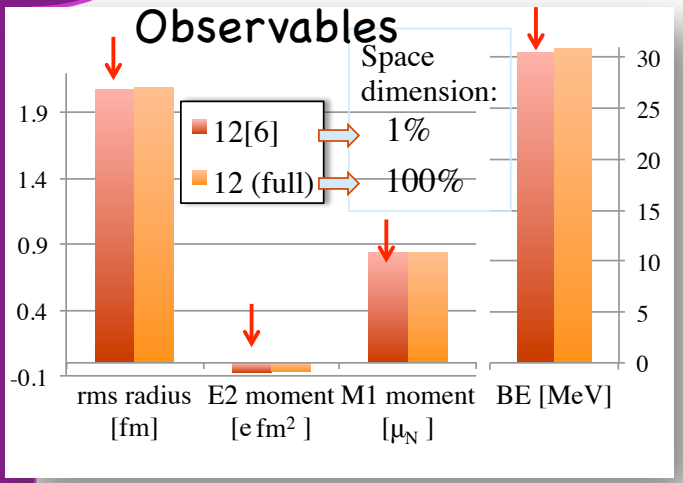


Launey et al., Prog. Part. Nucl. Phys. 89 (2016) 101;
Dytrych et al., Phys. Rev. C 91 (2015) 024326

Efficacy of SA-NCSM

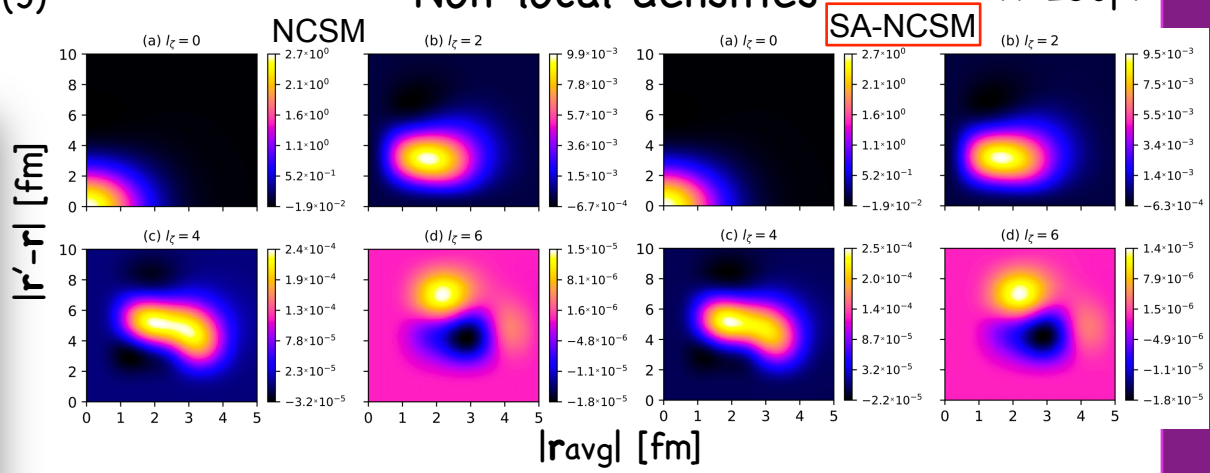
^{6}Li SA-NCSM, SU(3)

Observables

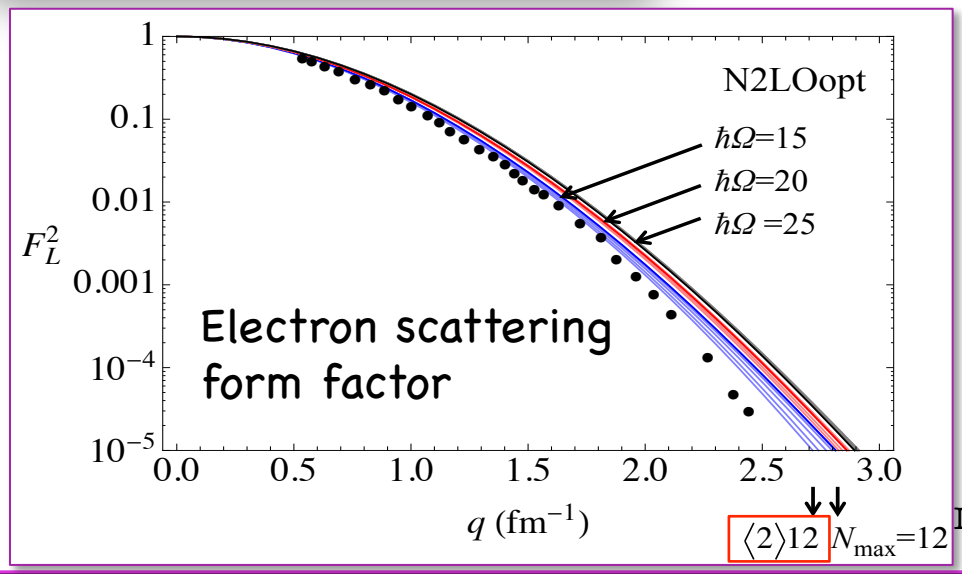


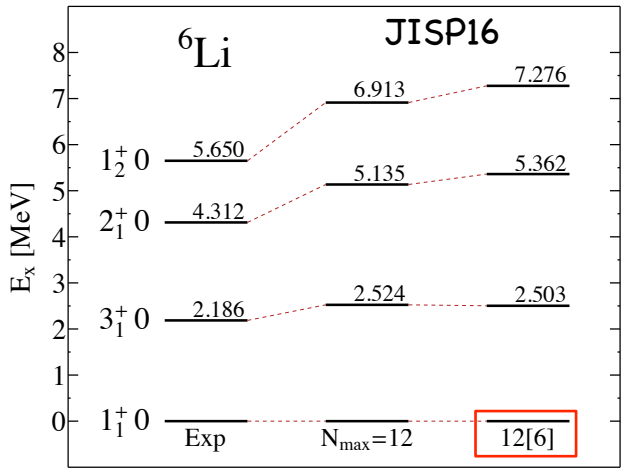
Non-local densities

N2LOopt



Burrows, Elster, Popa, Launey, Nogga, Maris, Phys. Rev. C 97 (2018) 024325





Launey et al., Prog. Part. Nucl. Phys. 89 (2016) 101;
Dytrych et al., Phys. Rev. C 91 (2015) 024326

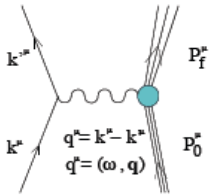
Coulomb sum rule

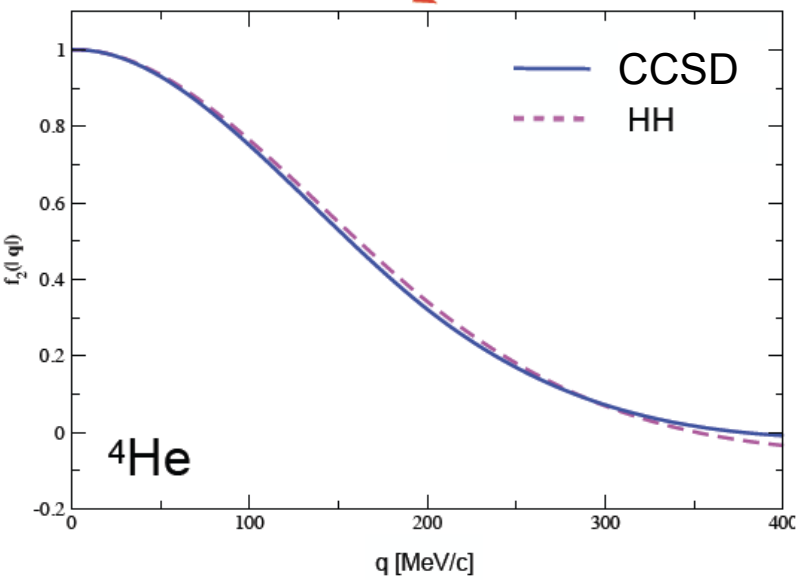
Total strength of inelastic longitudinal response function

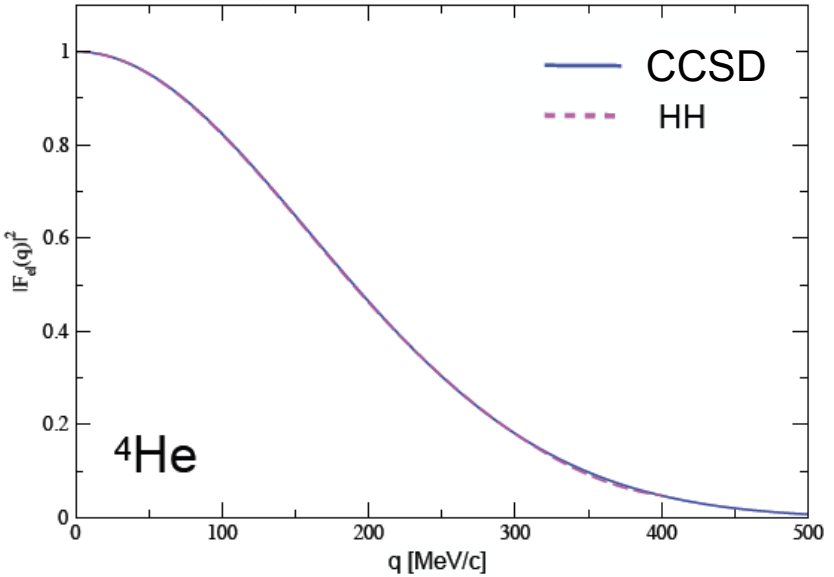
$$\mathrm{CSR}(q) = \int d\omega \; R_L^{in}(\omega, \mathbf{q}) \qquad R_L^{in}(\omega, \mathbf{q}) = \sum_f |\langle f|\rho(\mathbf{q})|\mathbf{0}\rangle|^2 \delta(\omega - \mathbf{E_f} + \mathbf{E_0})$$

$$\mathrm{CSR}(q) = Z + \langle 0| \sum_{i \neq j} e^{i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} |0\rangle - |F_{\mathrm{el}}(\mathbf{q})|^2 Z^2$$

$$\| \quad Z(Z-1) f_2(|\mathbf{q}|)$$







Bacca, Miorelli, Hagen, J. Phys.: Conf. Series **966** (2018) 012019

from Sonia Bacca

Coulomb sum rule

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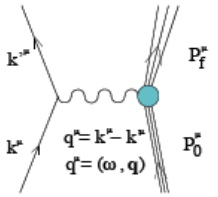
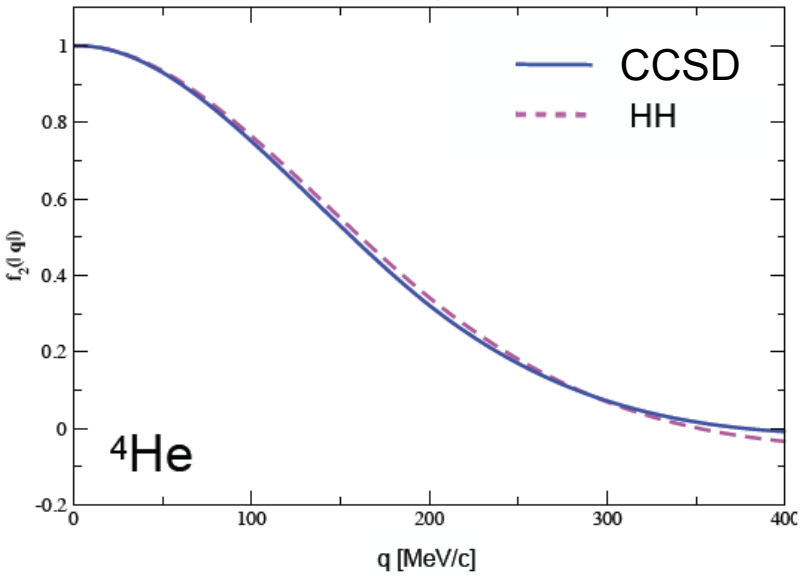
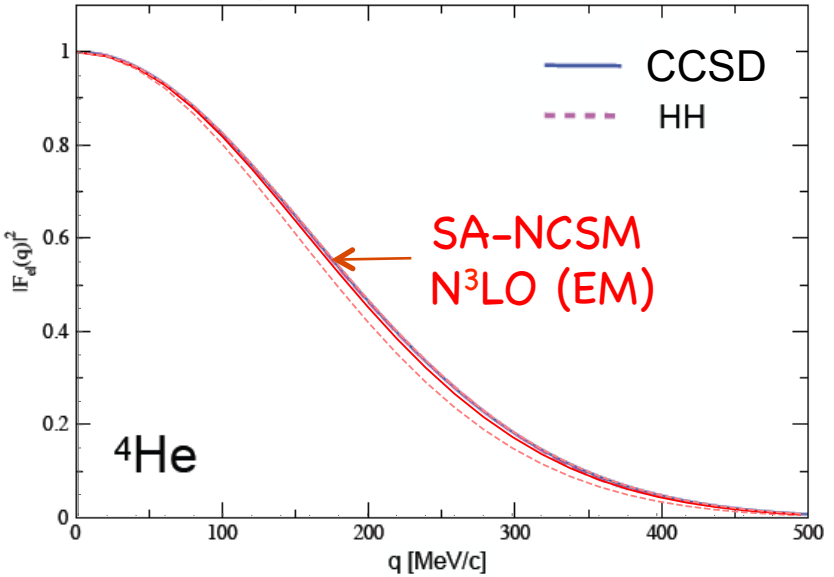
$$\mathrm{CSR}(q) = Z + \langle 0| \sum_{i \neq j} e^{i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} |0\rangle - |F_{\mathrm{el}}(\mathbf{q})|^2 Z^2$$

$$\| \quad Z(Z-1) f_2(|\mathbf{q}|)$$





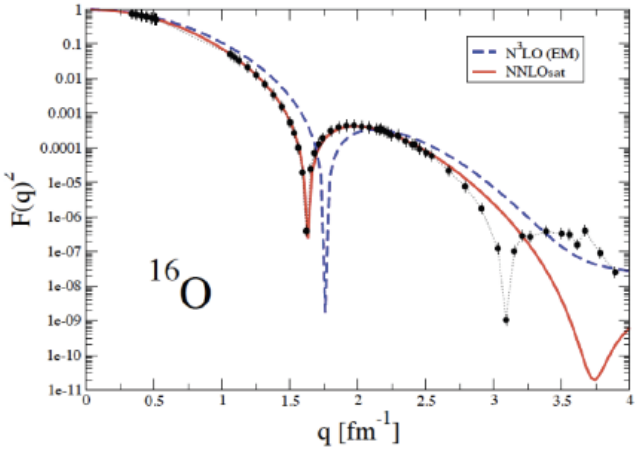


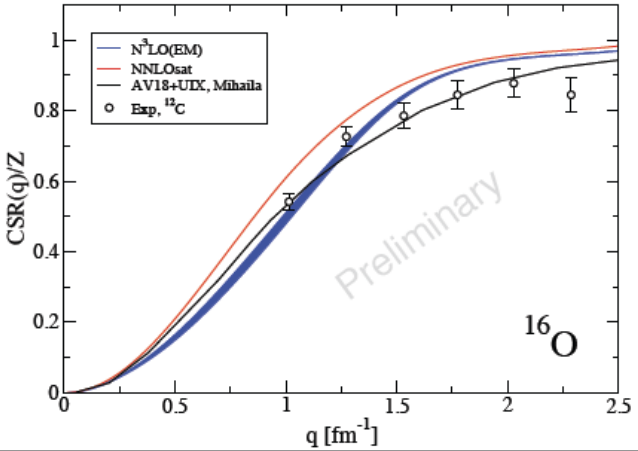
Bacca, Miorelli, Hagen, J. Phys.: Conf. Series **966** (2018) 012019

from Sonia Bacca

Coulomb sum rule

S. Bacca et al., in preparation (2018)



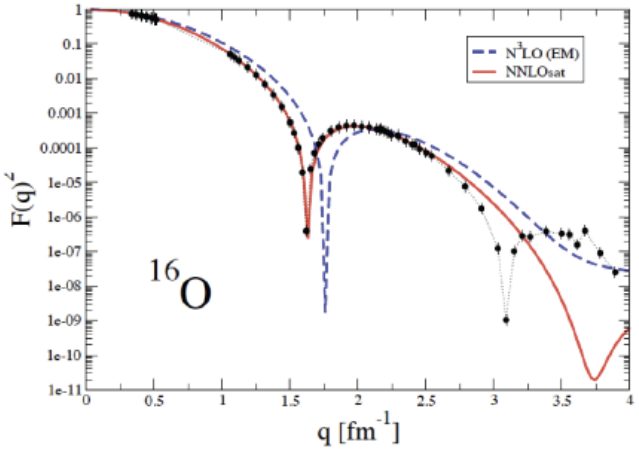


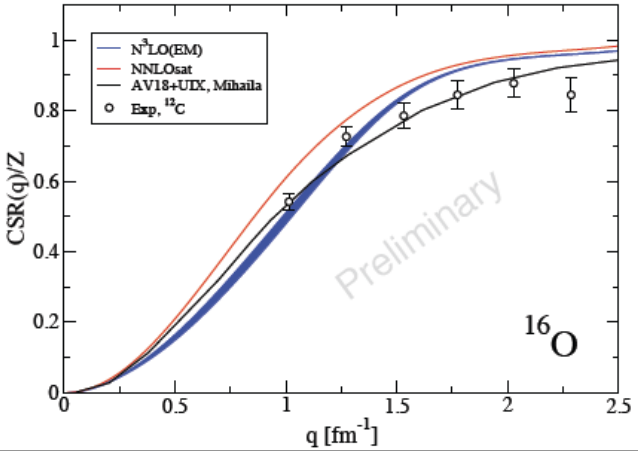
Bacca, Miorelli, Hagen, J. Phys.: Conf. Series **966** (2018) 012019

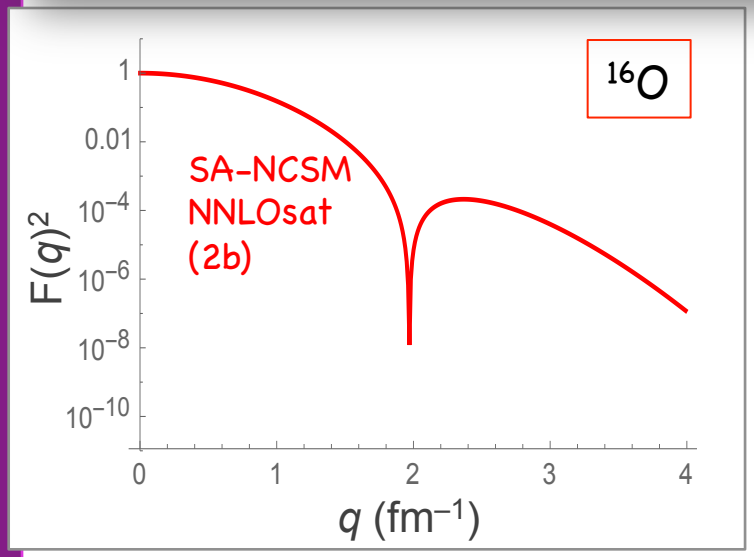
from Sonia Bacca

Coulomb sum rule

S. Bacca et al., in preparation (2018)

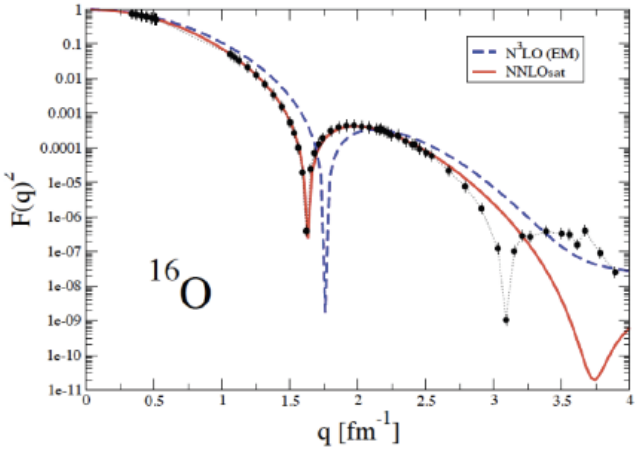


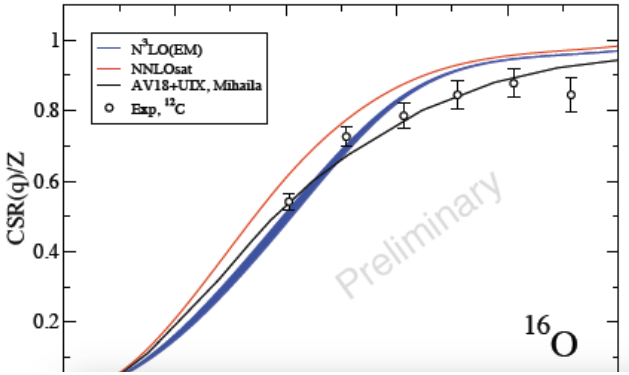


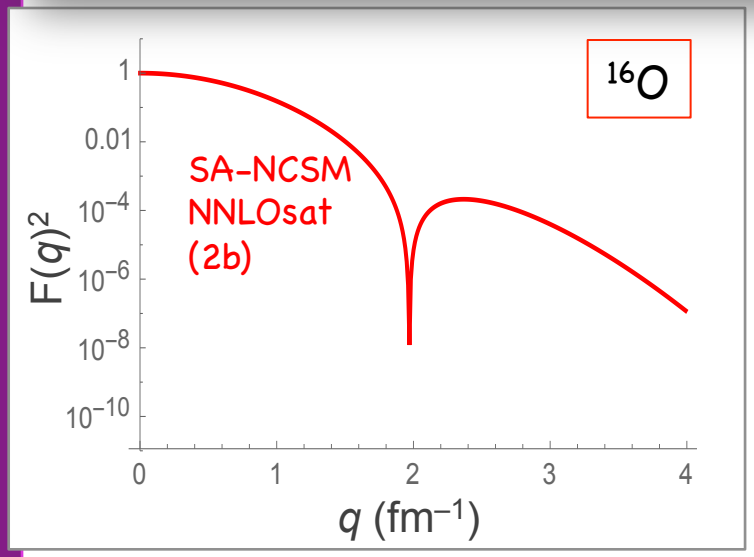


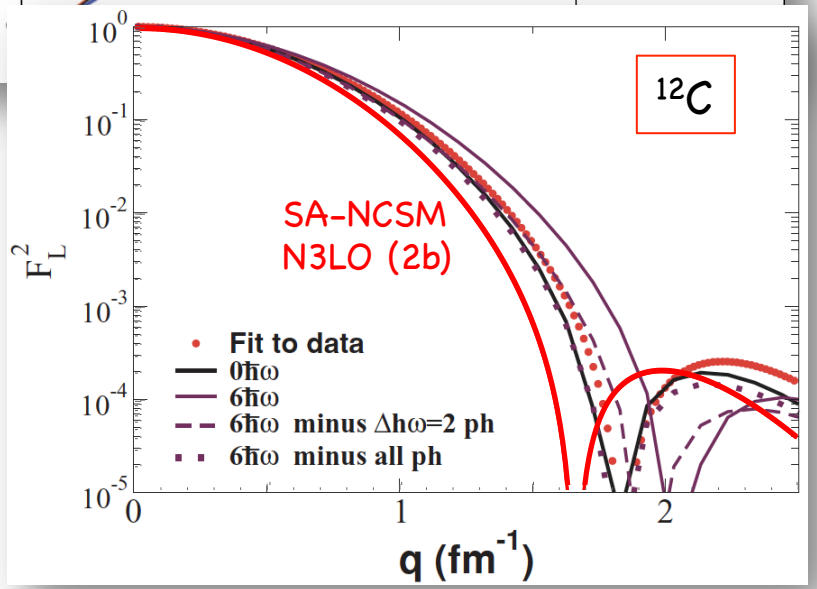
Coulomb sum rule

S. Bacca et al., in preparation (2018)







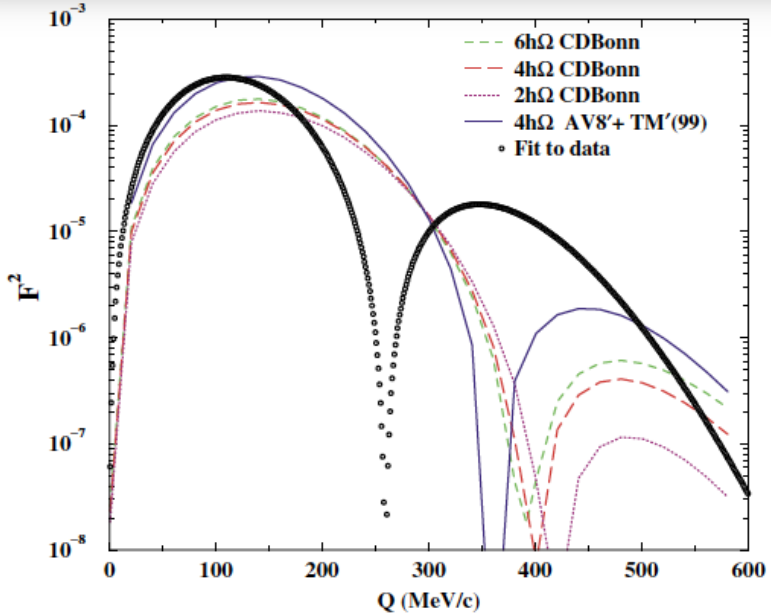


Hayes et al., PRC 81, 054301 (2010)

Outlook

TABLE II. Predicted weak interaction rates for the $^{12}C \rightarrow T = 1\ 1^+$ transitions. The units are 10^{-42} cm^2 for the (ν_e, e^-) DAR cross section, 10^{-40} cm^2 for the (ν_μ, μ^-) DIF cross section, and 10^3 sec^{-1} for muon capture.

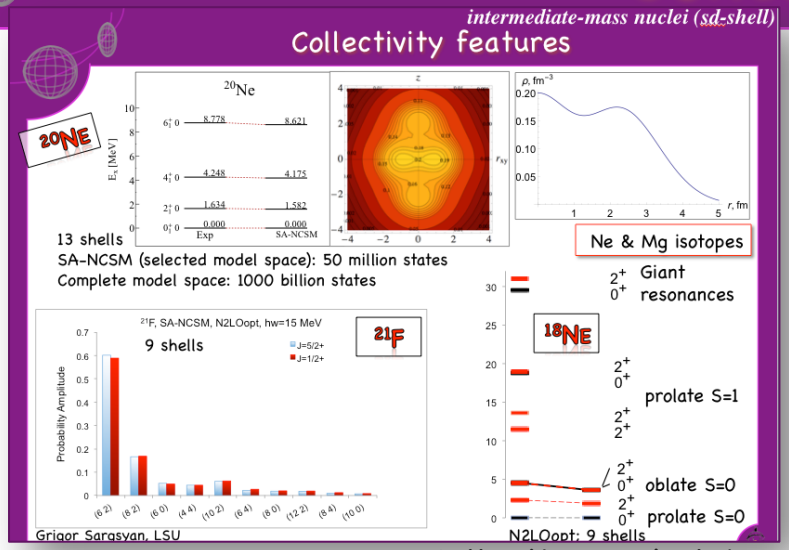
	CD-Bonn			AV8′ + TM′(99)	
Interaction	$2\hbar\Omega$	$4\hbar\Omega$	$6\hbar\Omega$	$4\hbar\Omega$	Experiment
(ν_e, e^-)	2.27	3.2	3.69	6.8	$8.9 \pm 0.3 \pm 0.9$ [19]
(ν_μ, μ^-)	0.168	0.275	0.312	0.537	$0.56 \pm 0.08 \pm 0.1$ [20]
μ-capture	1.46	2.07	2.38	4.43	6.0 ± 0.4 [21]



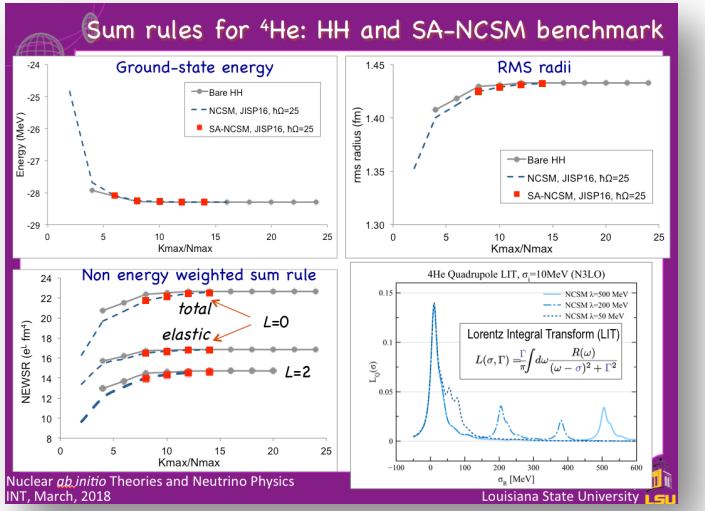
Hayes et al., PRL 91, 012502(2003)

- Improve earlier NCSM studies, use bare chiral potentials
- ^{40}Ar SA-NCSM calculations
- Calculate response functions from SA-NCSM with LIT

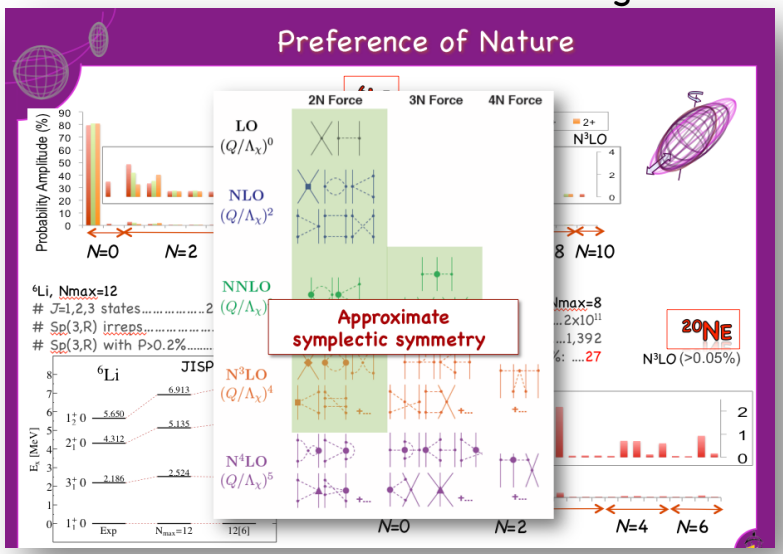
Conclusions



Collective and alpha clustering features in nuclei



SA-NCSM+LIT (with S. Bacca): sum rules and responses



Simple physics: "shape" + vibrations + rotations